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The Effect of Heat Treatment on Tensile, Fatigue and Fracture Resistance of ADC3, ADC10, and ADC12 Alloys

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Until recently, the solution heat treatment of conventional aluminum high pressure die cast (HPDC) parts has not been considered possible because the high temperatures involved cause surface blistering and dimensional instability. Following the development of a novel heat treatment procedure, these problems can now be avoided. As a consequence, the tensile properties of HPDC's can be much improved with little adverse effect on ductility. This paper extends the earlier work to report the effects of these new heat treatment procedures on the tensile, fatigue properties and fracture resistance of HPDC alloys ADC3, ADC10, and ADC12. Comparisons are made between as-cast, T4 and T6 conditions. It is shown that, as with wrought products, the fatigue lives of the alloys are related to their tensile strengths and, as a result, the fatigue resistance of the heat treated aluminum HPDCs is excellent. Fracture resistance, as determined by tear testing, is shown to be optimized in underaged or T4 tempers such that the fracture properties of heat treated HPDC's compare favorably with permanent mold cast 356-T6 (AC4C-T6) alloy.

Keywords: *High Pressure Diecasting, Heat Treatment, Fatigue, Fracture.*

1. Introduction

The composition ranges of the HPDC alloys ADC3, ADC10 and ADC12 are shown in Table 1. All have the potential to respond to age hardening and recent work has revealed a heat treatment procedure by which the problems of blistering and distortion in HPDC's can be avoided [e.g. 1,2]. As a result, large improvements in tensile properties have been demonstrated compared with the as-cast condition; in some cases values of 0.2% proof stress can be more than doubled.

Table 1 JIS Composition Limits of Some Heat Treatable HPDC alloys[1]

Alloy / w%	Si	Fe (max)	Cu	Mn	Mg	Ni (max)	Zn (max)	Sn (max)
ADC3	9.0-10.0	1.3	Max 0.6	Max 0.35	0.4 - 0.6	0.5	0.5	0.1
♣ ADC10	7.5 - 9.5	1.3	2.0-4.0	Max 0.5	Max 0.3	0.5	1	0.3
♣ADC12	9.6-12	1.3	1.5-3.5	Max 0.5	Max 0.3	0.5	1	0.3

♣: note ADC10Z and ADC12Z have max 3%Zn.

The modified procedure involves a severe truncation of the solution treatment stage, for which shorter times and lower temperatures are utilized. Due to the fast solidification rate and unique microstructures generated by the high pressure diecasting process, this procedure does still allow at least a partial dissolution of solute elements such as Cu and Mg. Modified solution treatment practices have been applied to ageing at room temperature (T4 temper) and elevated temperature (T6 temper). T7 tempers have also been investigated that involve ageing beyond peak properties at higher than normal temperatures. This is most commonly applied where a component is required to operate at elevated temperature (e.g. 100-120°C), such as that experienced in many automotive applications. As may be appreciated, there are also many other ageing procedures that may be used following the modified solution treatment procedures developed for HPDC's. The current paper briefly

[1] ADC3 is similar to the US specification for alloy A360. ADC10 incorporates US specification alloys A380 and C380. ADC12 incorporates US specification alloys 383 and A383.

summarises the outcomes of these novel heat treatment procedures and outlines their effects on tensile, fatigue, and fracture resistance of HPDC alloys ADC3, ADC10 and ADC12.

2. Experimental Methods

2.1 Casting

HPDC specimens were produced using a Toshiba horizontal cold chamber die-casting machine with a 250 tonne locking force, a shot sleeve with an internal diameter of 50 mm and a stroke of 280mm. The metal velocity at the gate was 82 m/s for tensile or fatigue samples, and 56m/s for plates used for tear testing.

2.2 Tensile samples

Cylindrical tensile test bars were produced following procedures detailed elsewhere [2]. Two cylindrical samples and one flat sample were prepared from each shot. Cylindrical samples used for tensile testing had a parallel section of 33mm and gage diameter of 5.55±0.1mm. Other tensile samples were machined from the same plates used for tear testing, as required by the tear test standard, ASTM B871. These samples had a gauge section ~10 mm wide, a parallel length of 30 mm, and a transition radius of 10 mm. The as-cast surfaces of the top and bottom of the plates were retained, and the samples were machined with the principal stress axis perpendicular to the direction of metal flow. All tensile samples in either configuration conformed to specification AS1391. As-cast cylindrical test bars were tested at a crosshead speed of 5mm/min., whereas those machined from plates were tested at 2mm/min. to correspond to the procedure for tear testing.

2.3 Tear test samples

HPDC plates for the manufacture of tear test specimens were 60x70x2 mm, from each of which one tensile specimen and one tear test specimen were machined. Tear test samples were prepared according to ASTM B871, and particular attention was made to ensure the notch radius was within the required specification (25 µm+/-12.7 µm). The as-cast surfaces of the top and bottom of the plates were retained. Plates were heat treated before machining samples. For each set of tests, five tensile and five tear test samples were taken in each heat treatment condition. Tear testing was conducted using standard procedures, with a crosshead speed of 2 mm/min. As for the tensile samples, the principal stress axis was perpendicular to the direction of metal flow.

2.4 Fatigue samples

Specimens were cylindrical, with a grip diameter of 13 mm, a parallel gauge section 8 mm long and 4.3 mm diameter. Following casting and heat treatment, the grip ends of the specimens were machined to 12 mm diameter to fit in the test grips, and the parting line on the gauge length was carefully removed with fine emery paper, taking care not to damage the remaining surface of the specimen. Axial pull-pull testing was done under force control at 60Hz over a range of stress levels at a stress ratio of R=0.1 (where R is the ratio of minimum to maximum stress).

2.5 Alloys and heat treatment

The composition ranges of the alloys tested were within the specifications for ADC3, ADC10 and ADC12, and the compositions of these alloys are presented in Table 2. Two ADC10 alloys were examined here because the variation in Mg content produces different combinations of strengthening precipitates and might therefore produce different mechanical properties [1-4]. Heat treatment of these alloys was conducted following procedures developed in earlier studies [1-4] and, for these respective alloys, specific details of the procedures will be given within the text. Solution treatment temperatures were 505ºC for Alloy ADC3 and 480ºC for alloys ADC10 and ADC12. Immersion

Table 2 Compositions of the alloys examined

Alloy / w%	Si	Fe	Cu	Mn	Mg	Zn
ADC3	9.3	0.79	0.59	0.19	0.58	0.49
ADC10 #1	9	0.86	3.1	0.14	0.1	0.53
ADC10 #2	9.1	0.86	3.18	0.19	0.29	0.6
ADC12	10.7	0.73	1.74	0.15	0.22	0.51

times were restricted to 15 minutes for the tensile and fatigue specimens and 10 minutes for the tear test plates. For the T4 tempers, all alloys were aged for 14 days at 25 ºC prior to testing. For the T6 tempers, the ageing conditions were 2.5h at 180ºC for ADC3 and 24h at 150ºC for the other three alloys.

3. Results and Discussion

3.1 Tensile properties

Tensile properties for individually cast cylindrical test bars of the four alloys in the as-cast, T4 and T6 tempers are shown in Fig. 1. All display roughly similar tensile properties in the as-cast condition, with 0.2% proof stress values ranging from 165 MPa for the ADC12 alloy to 189 MPa for the ADC10#2 alloy. Tensile strengths ranged from 308 MPa for the ADC12 alloy to 358 MPa for the ADC10#2 alloy. Elongations were also similar for each. When aged to a T4 temper, the ADC3alloy exhibited little change to the 0.2% proof stress or tensile strength, whereas elongation was raised from 4.6% in the as-cast condition to 9%. For the ADC10 and ADC12 alloys, the 0.2% proof stress, tensile strength and elongation were all increased following a T4 temper. Using a T6 temper significantly increased the 0.2% proof stress and tensile strength of all four alloys, but caused a small decrease in elongation below the values for the as-cast condition. Increases for the 0.2% proof stress, for example, ranged from 75% above the as-cast value for the alloy ADC12, up to 100% for ADC10#2.

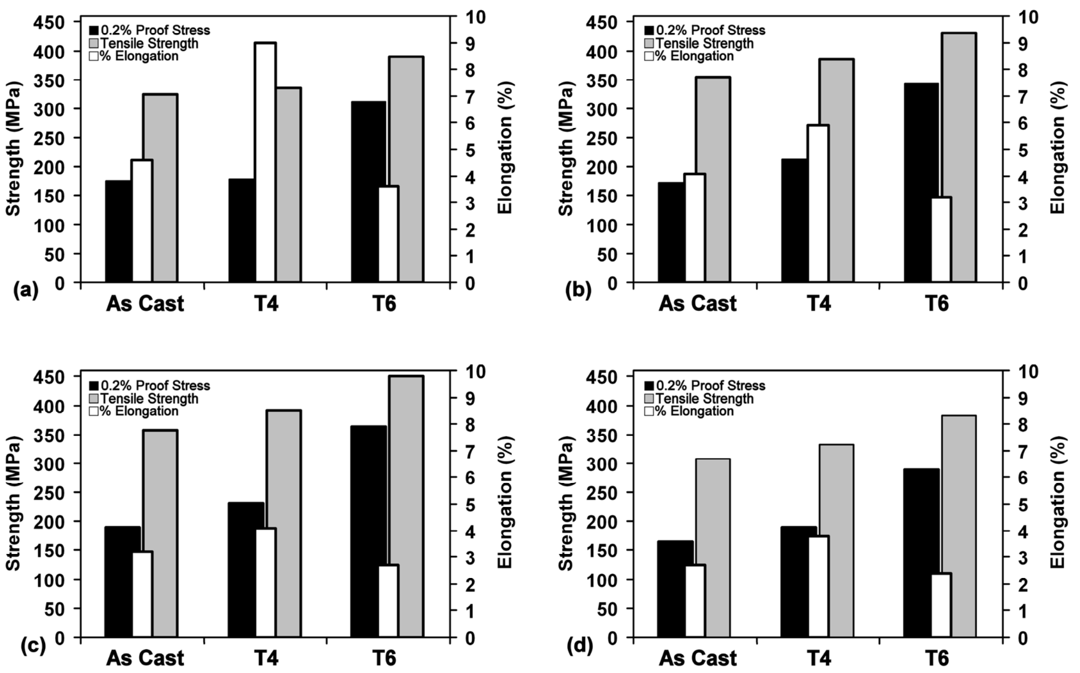

Fig. 1. Tensile properties of the four alloys made from cylindrical tensile test bars examined in as-cast, T4 and T6 tempers. (a), ADC3, (b), ADC10#1, (c) ADC10#2, (d) ADC12.

It is also important to note that higher Cu versions of ADC10 or ADC12 alloys produce still higher properties than those recorded here (e.g.>400 MPa 0.2% proof stress) [1-3]. The actual tensile properties achieved in a heat treated diecasting are strongly dependent not only on the composition (i.e. Cu and Mg content), but also on the solution treatment and ageing temperatures used [3]. An example of the effect of solution treatment temperature on the tensile properties of the ADC12 alloy tested when aged to peak strength at 150ºC is shown in Fig. 2, and indicates clearly the influences on tensile properties. From Fig. 2, it may also be noted that even solution treatment temperatures as low as 430ºC for only 15 minutes produces a significant response to heat treatment (as-cast properties for

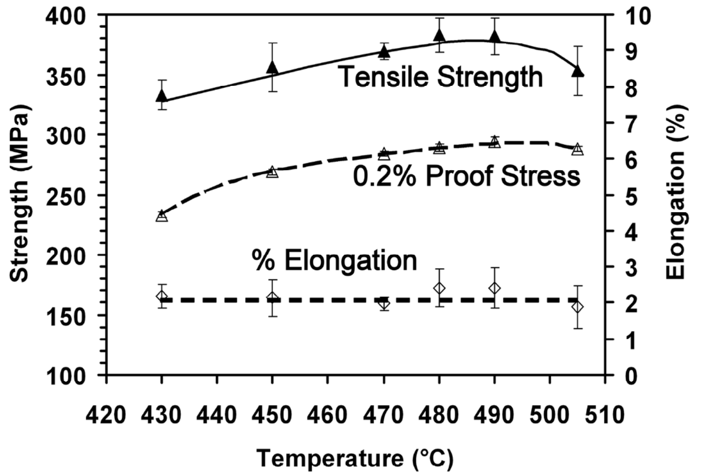

Fig. 2. Tensile properties of the ADC12 alloy studied as a function of solution treatment temperature.

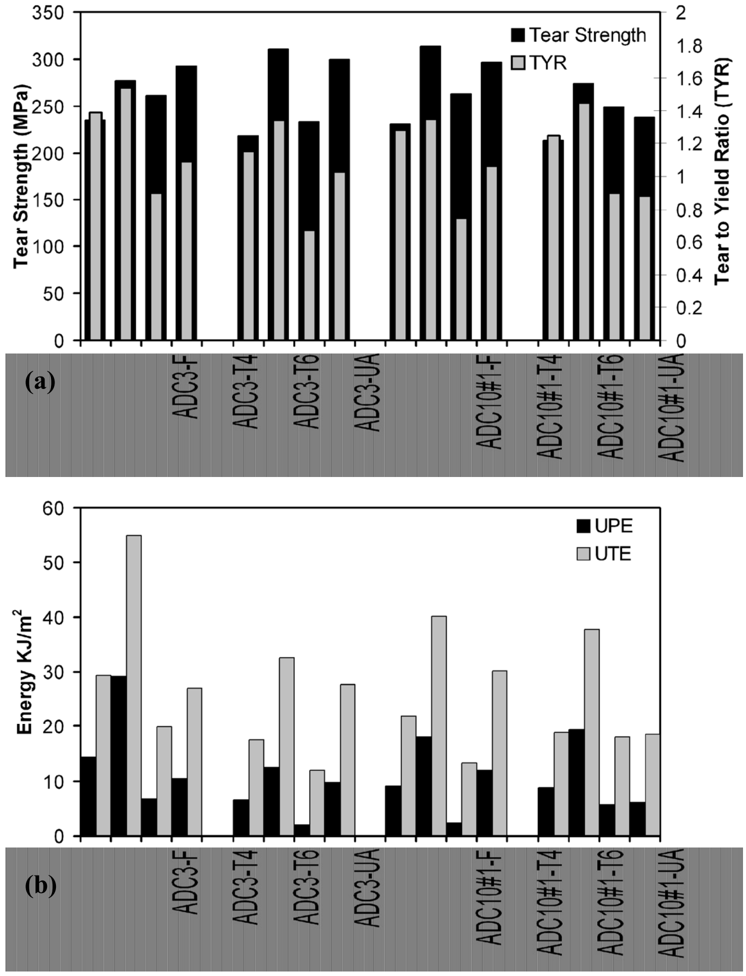

Fig. 3. a) shows tear strength and tear-to-yield ratio for the four alloys; b) shows the unit propagation energy, (UPE) and unit total energy (UTE).

comparison are provided in Fig. 1d). Consistent with results for other alloys, the tensile properties are maximised at 480-490ºC. At higher temperatures, minor blistering and the formation of internal porosity become more prevalent suggesting there is no specific advantage to following this practice.

3.2 Fracture resistance

The results of tear testing the four alloys in as-cast, T4 and T6 tempers are shown in Fig. 3a and b. In addition to the as-cast (F), T4 and T6 tempers, an underaged T6 temper (UA) was also included for comparison because it has been found [4] that UA usually produces an optimal combination of tensile and fracture properties. Although UA usually results in a 10-20% decrease in 0.2% proof stress, the fracture properties may be significantly improved. Fig. 3a shows the tear strength and tear-to yield ratio for each condition whereas Fig. 3b shows results for the unit propagation energy and unit total energy derived from the testing. The corresponding tensile properties for samples machined from the plates tested are provided in Table 3.

In the T4 tempers, the fracture properties are substantially better than for all other conditions, which, when combined with moderate increases to tensile properties, shows the very favourable outcome of using the T4 temper where fracture resistance or energy absorption are important. In particular, it should be noted that, for example, results of a typical permanent mold cast A356 alloy [5] are reported to display tensile properties of 218 MPa 0.2% proof stress, 266 MPa tensile strength and 2.8% elongation. Tear properties were: tear strength of 258 MPa, a TYR value of 1.2, a UPE of 14 KJ/m^2 and a UTE of 24.5 KJ/m^2. The values determined in the current study for the HPDC compositions in T4 or some UA tempers were equivalent to or better than those reported for A356-T6.

Table 3 Tensile properties from samples machined from plates used for tear testing.

Alloy and Temper	0.2% Proof Stress	Tensile Strength	% Elongation
ADC3-F	169	289	2.8
ADC3-T4	180	297	5.1
ADC3-T6	292	335	1.7
ADC3-UA	269	330	2
ADC10#1-F	190	300	1.9
ADC10#1-T4	232	338	2.4
ADC10#1-T6	350	393	1.2
ADC10#1-UA	290	362	2
ADC10#2-F	181	312	2.5
ADC10#2-T4	232	336	2.7
ADC10#2-T6	349	396	1.6
ADC10#2-UA	281	433	1.7
ADC12-F	170	275	1.8
ADC12-T4	189	276	2
ADC12-T6	277	300	0.9
ADC12-UA	271	323	1.4

3.3 Fatigue resistance

Values of axial fatigue lives for the four alloys in as-cast and T6 conditions were determined using standard procedures and the results are shown in Fig. 4. Here it should also be noted that for Fig. 4(b) the results presented are the combined results of the two ADC10 alloys, since there was only a small difference in Mg content. It will be seen that the fatigue life of the T6 treated HPDC's is high, with a fatigue endurance limit greater than 250 MPa being observed for all alloy types when heat treated to the T6 temper. It should also be noted that both ADC3 and ADC12 display superior fatigue test results when compared to the ADC10 alloys. For the former two alloys in the T6 temper, the fatigue limit is close to 270 MPa. These higher fatigue properties are present despite the fact that the 0.2% proof stress values of these alloys are lower.

Table 4 shows the ratios of fatigue limit to yield stress and tensile stress (taken from testing of the fatigue specimens), for both as-cast and T6 treated conditions. It is interesting to note that the ratios of fatigue endurance limit to tensile strength for alloys ADC3 and ADC12, in both as-cast and T6 tempers were higher than the ratios for the two ADC10 alloys in the same conditions. Similarly, the absolute fatigue limits for the former two alloys are also better than the higher strength ADC10 alloys. Here it may also be noted that, for the first two alloys aged to a T6 temper, the dominant precipitate phases are L and Q' ($Al_5Cu_2Mg_8Si_6$), whereas for the other two, ageing mainly results in the formation of the θ' phase Al_2Cu. These differences may indicate that precipitate type has some effect on fatigue lifetimes. The possible role of precipitate type on fatigue of these diecast

Table 4 Endurance limit† at 10^7 cycles, in absolute terms and in terms of tensile properties

Alloy	Temper	Endurance Limit MPa)	(Endurance Limit) ÷ (Proof stress)	(Endurance Limit) ÷ (Tensile strength)
ADC3	as-cast	205	1.32	0.66
	T6	270	0.9	0.7
ADC10#1	as-cast	210	1.17	0.59
	T6	250	0.71	0.54
ADC10#2	as-cast	210	1.17	0.62
	T6	250	0.67	0.55
ADC12	as-cast	200	1.43	0.64
	T6	270	0.97	0.65

† Estimated from the S-N curves generated.

compositions requires further investigation, but may arise due to the influence of the L and Q' phases on the rate of work hardening [3].

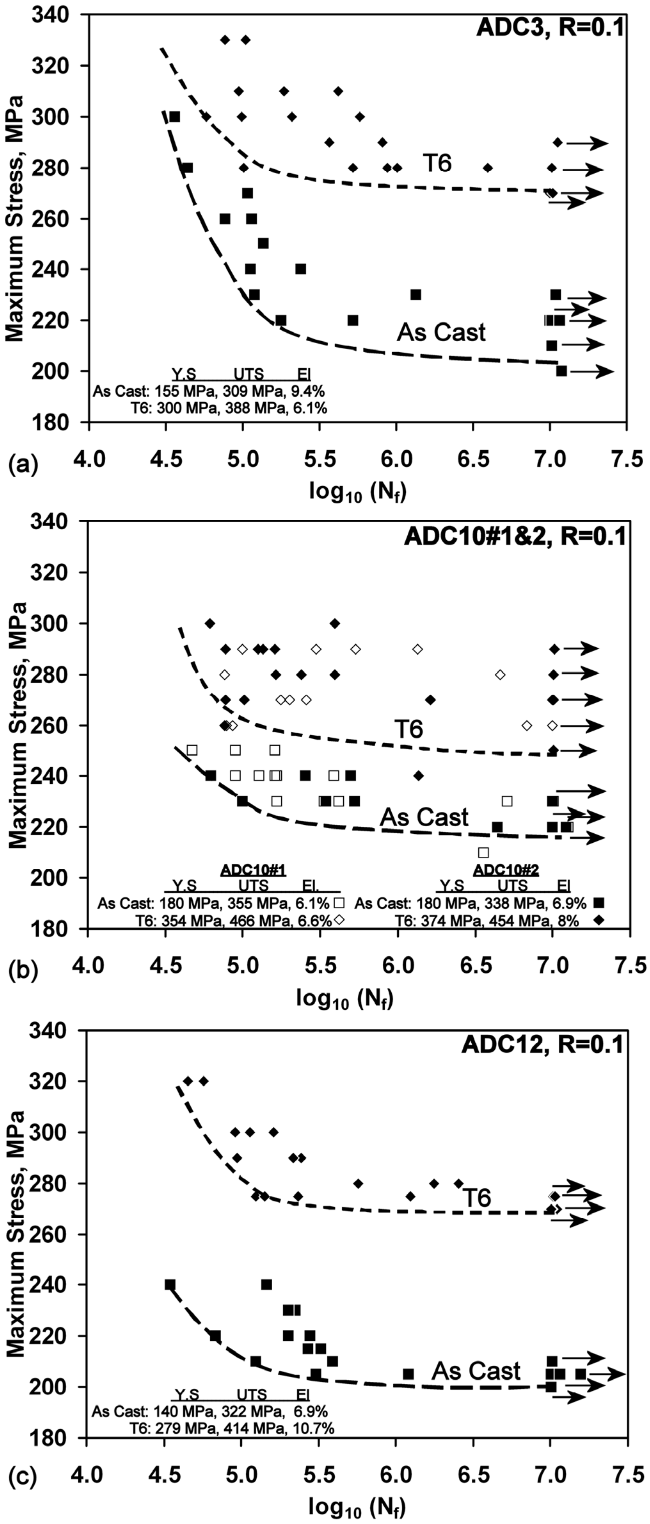

Fig. 4. Axial S-N_f data, R = 0.1. in as-cast and T6 conditions (a) shows ADC3, (b) shows ADC10 and (c) shows ADC12. Data at 10^7 cycles are runouts.

4. Conclusions

1. Conventionally produced high pressure diecastings based around the compositions for ADC3, ADC10 and ADC12 may be successfully heat treated to develop high mechanical properties.
2. By heat treating to a T4 temper, values of 0.2% proof stress, tensile strength and elongation may be increased simultaneously. In the alloy ADC3 aged to a T4 temper, there was little change to the 0.2% proof stress or tensile strength, but the elongation was nearly doubled from 4.6 to 9%.
3. In a T6 temper, tensile properties may be increased as much as 75-100% for 0.2% proof stress values, with only a small decrease in elongation compared to the as-cast condition.
4. The fracture properties of heat treated high pressure diecastings may be significantly improved by the use of T4 or underaged T6 tempers. In particular, underaged T6 tempers offer excellent combinations of tensile and fracture properties in most alloys, for only a small sacrifice in strength compared to the fully hardened T6 condition.
5. Fatigue properties of heat treated HPDC's are excellent. For ADC3 or ADC12 alloys, the fatigue limit may be as high as 270 MPa. In both the as-cast and T6 tempers, these alloys show higher ratios of fatigue endurance limit to tensile strength and in T6 tempers, display higher absolute fatigue properties.

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